Experimental data from the Braunschweig FACE studies on wheat growth responses to elevated CO_2 in combination with nitrogen supply or infrared warming during grain filling

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Abstract: This paper is about data from a FACE experiment with winter wheat (Triticum aestivum, c.v. Batis) carried out over two years at Braunschweig, Germany. The experimental variants included firstly a study on the interaction of two levels of CO_2 (393, 600 ppm) and three levels of nitrogen (N) fertilization (ca. 40, 190 and 320 kg N ha^{-1}) and secondly a study on the interaction of these CO_2 treatments and three levels of infrared warming during grain filling (ambient, ca. +1.5°C and +3°C). In the second study N supply was only ca. 190 kg N ha^{-1}. The datasets of the two studies assembled herein contain data on weather, management, soil condition, soil moisture, phenology, dry weights and N concentrations of the plant (leaves, stems ears), green area index, stem reserves, final grain yield and yield components as well as canopy temperatures (this only applies to the second study). Moreover, the dataset contains measured values on important grain quality traits including concentrations of flour proteins, of key minerals and baking quality variables of the CO_2 x N study. Most of the experimental findings have already been published in scientific journals. Data provided herein are suited to validate the interaction of elevated CO_2 concentration and either N supply or high temperature during grain filling in wheat growth models.

Keywords: winter wheat, free air CO_2 enrichment, FACE, nitrogen fertilization, warming, infrared warming, biomass, plant N concentration, grain yield, grain nitrogen, grain quality, water use.

1 BACKGROUND: Climate change due to rising atmospheric CO_2 concentration and associated increase in temperature, heat waves and drought periods will have important implications for global food production (IPCC, 2013). A variety of field studies have already been conducted to investigate the effect of elevated CO_2 concentration (eCO_2) on wheat and such resultant datasets (e.g., Kimball et al., 2017, 2018) have been used by crop modelers to assess the effects of climate change on global wheat production (Rosenzweig et al., 2014; Asseng et al., 2019). However, there are still uncertainties particularly regarding the interaction of CO_2 and N supply on wheat growth as well as the effect of eCO_2 on plant N dynamics (Rosenzweig et al., 2014; Vanuytrecht & Thorburn, 2017).On the other hand, the beneficial effect of eCO_2 on stomatal conductance has been well documented in many experiments (Ainsworth & Rogers, 2007). However, although the consequence of this effect for seasonal water use has scarcely been investigated in field studies (Kimball, 2016), it has been predicted in several modelling studies (Cammarano et al. 2016; Deryng et al., 2016; Kersebaum et al., 2016). Moreover; another important issue in the context of future climate change responses of crops and particularly wheat is the effect of increasing temperature including altered temperature regimes during the growing season and the interaction with eCO_2. While this has been studied experimentally under irrigated desert conditions (Ottman et al., 2012), such data obtained from field studies under temperate climate conditions are hardly available.

We have run a two year FACE experiment with winter wheat and analyzed firstly, the interaction of eCO_2 and N fertilization and secondly, the interaction of eCO_2 and experimental warming during grain filling on plant growth, including grain yield, grain quality, plant N dynamics and water use. Most of the results of these studies have already been published in scientific journals (Dier et al., 2018a, 2018b, 2019, 2020; Manderscheid et al., 2018) or conference proceedings (Luig et al., 2016). This paper contains most of the experimental soil and plant datasets of these experiments.

2 METHODS

2.1 EXPERIMENTAL FIELD SITE: The experiments were conducted on the experimental field at the Johann Heinrich von Thünen-Institute, Federal Research Institute for Rural Areas, Forestry and Fisheries, Braunschweig, South-East Lower Saxony, Germany (52°18' N, 10°26' E, 79 m a.s.l.). The soil is a Luvisol of a loamy sand texture (69% sand, 24% silt, 7% clay) in the plough horizon (0-30 cm). The soil profile (--30 cm Ap, --15 cm Al, --15 cm Bt, >60--70 cm CII) is limited because the greatest part of the roots was in the plough layer and roots hardly penetrated deeper soil layers (Pacholsky et al., 2015). The lower layers, in particular >70 cm, are characterized by a coarser soil texture (almost pure sand) and are structured by the succession of thin silt/clay layers. The plough layer has a pH of 6.5 and a mean organic carbon content of 1.4% and a total N content of approx. 0.1%. The drained upper (0.01 MPa soil water tension) and lower limits (1.5MPa water tension) in soil water content were 23% and 5%, respectively. Thus, the soil has a volumetric plant available water content of ca. 18% in the plough layer, which decreases slightly with increasing soil depth.

2.2 CO_2 TREATMENTS: Three circular plots (each with a diameter of 20 m) were equipped each with a free air CO_2 enrichment apparatus including vertical vent pipes and CO_2 injection driven by a blower (Lewin et al., 1992). These rings comprised what is termed eCO_2 treatment or FACE rings. Three further circular plots without the CO_2 enrichment apparatus were used as control treatment (=aCO_2, 393 ppm, ambient rings). The target CO_2 concentration in the FACE rings was set to 600 ppm during daylight hours (i.e. daylight solar altitude θ >-0.833°). CO_2 enrichment was interrupted at wind speeds > 6 m s^{-1} or if temperature fell below 5°C. The FACE and ambient rings were set up after crop emergence and removed after final harvest. The CO_2 enrichment lasted from the three leaf stage in March (31th March in 2014, 12th March in 2015) until end of grain filling in July (21st July in 2014, 24th July in 2015).

2.3 CROP CULTIVATION: Agricultural management measures were performed according to local farm practice and included plough tillage, mineral fertilization and pesticide treatment. Fertilizers during the growing season were added based on soil analysis in springtime. Oat was grown as a cleaning crop in 2013. Winter wheat (Triticum aestivum L. variety "Batis") was sown in late autumn of 2013 and 2014 at a seeding depth of 3-4 cm and with a density of 380 kernels m^{-2}. Each of the six circular main plots (20 m diameter) was separated by a 1 m wide track into a northern and southern half (Fig. 1). The warming study was run in the northern, the nitrogen fertilization study in the southern ring half. During the growing season application of plant protection measures and nutrients were performed with a common field sprayer (32 m wide).

2.4 NITROGEN FERTILIZATION STUDY (CO_2 x N): In each of the three FACE and ambient rings four subplots (3 m×5 m) with different N fertilization (N1, N2, N3, N2A) separated by a narrow path (0.5 m) were randomly established in the southern ring half (Fig. 1). When the whole experimental field was fertilized with ammonium nitrate / urea solution by the field sprayer this subplot area (ca. 14 m x 5 m) was covered with a tarpaulin. Immediately afterwards, the tarpaulin including the not applied liquid fertilizer was removed and three subplots (N1, N2, N3) were fertilized by hand with solid calcium ammonium nitrate. The N treatments comprised three levels of calcium ammonium nitrate: N1 (deficient) with 40/35 kg N ha^{-1}, N2 (adequate) with 180/200 kg N ha^{-1} and N3 (excessive) with 320 kg N ha^{-1} in 2014 and 2015, respectively. N2A was fertilized only with ammonium-N (Dier et al., 2018b) and data of this treatment are not shown here. Application of the N fertilizer was split into four dates from early leaf growth until anthesis in all treatments.

2.5 INFRARED WARMING STUDY (CO_2 x T): In each northern semicircle of the three FACE and ambient rings three small circular subplots (1.3 m diameter) were established (Fig. 1) and two of them were equipped with a T-FACE-system for increasing canopy temperature as described by Kimball et al. (2008). The T-FACE-system consisted of a hexagonal array of six infrared ceramic heaters (each with a maximum power of 1000 W) regularly adjusted to a height of ca. 80 cm above the wheat canopy and allowing the warming of a circular canopy area of 130 cm diameter. Canopy temperature on control and heated plots were recorded with Apogee infrared radiometers. These data were used by dataloggers to modulate the output of the heaters to achieve two warming levels (T1 and T2) above ambient (T0). The subplots for the control temperature treatment (T0) were equipped with a hexagonal array of wooden dummy heaters wrapped by an aluminum foil in 2014. As there was no significant difference (in canopy temperature, grain yield parameters) between field plots with and without dummy heaters, in 2015 control temperature subplots were not equipped with dummy heaters. There were two heating levels during grain filling: T1 with ca. +1.5°C and T2 with ca. +3°C. In 2014 and 2015, the heating (24h per day) was started 13 and 5 days after anthesis and lasted 29 and 32 days, respectively.

2.6 Irrigation: At the field site crop growth can occasionally be limited by water availability in the summer due to low field capacity. In order to prevent confounding effects resulting from drought stress, irrigation was implemented to keep volumetric soil water content in the range of 14–21% (50–90% of field capacity). Irrigation was adapted to the differing water demand of the different CO_2 x N (Manderscheid et al., 2018) and the different CO_2 x T treatments. Irrigation of the small individual plots of the CO_2 x N study in the southern half-ring (Fig. 1) was mostly done with a hand shower. The whole area of the northern half-ring containing the subplots of the CO_2 x T study was irrigated with a circle sprinkler over the whole season in 2014. The small subplots of the T1 and T2 treatment were additionally watered with a hand shower during the grain filling period if necessary. In 2015 the circle sprinkler was used only until mid of May and thereafter irrigation of all individual treatments was done with a hand shower. This irrigation practice was more time-consuming but more precise than the use of circle sprinklers.

FIGURE 1: View of the trial field with three circular main plots at ambient (a1–a3) and at elevated CO_2 (e1-e3). In the foreground the ambient ring a3 with the spatial arrangement of four subplots (3 m x 5 m) with different N supply (N1, N2, N3; N2A) and the three hexagonal arrays (diameter 1.3 m) with heaters for the warming treatments (T1, T2) and with dummies (T0) is shown.

2.7 MEASUREMENTS

2.7.1 WEATHER: Air temperature, global radiation and precipitation measured at 2 m height close to the experimental field site (<500 m) were provided by the German Weather Service.

2.7.2 SOIL MOISTURE: Soil water content (SWC) was recorded with TDR-sensors (from IMKO, Ettlingen, Germany), which had measuring rods of 16 cm length. SWC was measured in the 0-0.2m soil layer (with a hand held sensor vertically put into the ground) and 0.2-0.4m soil layer (with a buried sensor placed at a 45-degree angle in ca. 25-35 cm depth). Measurements were done approximately twice per week and in all replicates of the CO_2 x N study and of the CO_2 x T study, respectively. The average of SWC in the 0-0.4m soil profile was used to control water availability, irrigation and plant water use (see Manderscheid et al., 2018).

2.7.3 CANOPY TEMPERATURE: Canopy temperature was measured with Apogee infrared radiometers as described by Kimball et al. (2008) in all 18 replicates of the CO_2 x T study from the start until the end of the heating treatment.

2.7.4 CROP DATA OF THE CO_2 x N STUDY: Plant samples were taken at five dates (1st node stage, flag leaf stage, anthesis, milk-ripe stage and grain maturity), separated into different fractions and used for measuring their dry weights and areas where appropriate (see Dier et al., 2018a). Moreover, N concentration was determined in all plant fractions (leaves, stems, ears, grains; see Dier et al., 2019).The stem fraction was further used for measuring water soluble carbohydrate concentration and calculation of stem reserves (see Manderscheid et al., 2009). A few days after anthesis, weekly measurements of individual grain weight were started and continued until maturity. From each replicate subplot 10 (2014) or 15 ears (2015) were harvested. The ears were dried at 105°C to constant weight, subsequently threshed by hand and the single grain weight was calculated after measuring total grain weight and grain number of the sample. Grain quality was examined by measuring the concentrations of different flour proteins (albumins/globulins, gliadins and glutenins), of S, Fe, Zn, and baking quality (dough water absorption, dough development time and loaf volume) as described in Dier et al. (2020). Plant water use over the main growing period was calculated from rainfall, irrigation and change in soil water content (Manderscheid et al., 2018). Also, calculation of water use efficiency was carried out by using the total above ground biomass produced during this period.

2.7.5 CROP DATA OF THE CO_2 x T STUDY: From the control subplots without heating (T0) plant samples were taken at five dates similar to the procedure applied in the CO_2 x N study. From treatments T1 and T2 whole plant samples were taken only at grain maturity. Final harvest area of the T1, T2 and the T0 treatment with dummies in 2014 comprised only 0.4 m^2, and that of the T0 without dummies 1.8 m^2. Concentration of N and water soluble carbohydrates were determined in all available plant fractions (leaves, stems, ears, grains). Samplings for analysis of grain growth were done in the same manner as done in the CO_2 x N study. These data have been used to calculate grain filling rate and grain filling duration (Luig et al., 2016).

2.8 ANOMALIES DURING THE WHOLE EXPERIMENTAL PERIOD: Two anomalies occurred in the growing season of 2015. Heavy rainfall on 5th July caused lodging of the plants grown under excess N supply (N3). To minimize lodging effects on grain growth, affected plants were erected by means of a rope net until final harvest. Plants were regularly examined for fungal infestations (Meyer, 2019). At the milk stage in 2015, infestations with *Gaeumannomyces graminis* were detected. To overcome this problem at final harvest, infested plants were sorted out followed by counting the infested and healthy plant fractions. The maximum share of infested plants of a subplot was less than 20%. Yield variables were determined on the basis of the fraction of healthy plants and were then normalized to total plant number (healthy+infested plants).

3 DATA FORMAT AND STRUCTURE: All data are in the EXCEL file „wheat data.xlsx". This file contains 17 worksheets and their specific data are listed in Table 1.

Table 1	
Worksheet name	**Content**
data files & abbreviations	Name of the data files, abbreviations and units
TRNO definition	Code and definition of the different treatments
soil properties	Drained upper and lower limit of water content in 0-60 cm depth
weather2013	15-minute average weather data (temperature, radiation, humidity, wind speed, rainfall; measured at 2 m height, nearby the FACE field (<500 m)) for 2013
weather2014	15-minute average weather data for 2014
weather2015	15-minute average weather data for 2015
canopy_T2014	5-minute average of canopy temperature during heating in 2014
canopy_T2015	5-minute average of canopy temperature during heating in 2015

Table 1 Contd.	
Worksheet name	**Content**
management	Management measures (ploughing, sowing, fertilization, pesticide application, irrigation, schedule of heating)
soil moisture2014	Soil water content measured with TDR sensors in 2014
soil moisture2015	Soil water content measured with TDR sensors in 2015
phenology	Phenological data of both experimental years
growth2014	Growth data of the 1st experimental growing season (2014)
growth2015	Growth data of the 2nd experimental growing season (2015)
grain growth2014	Data on single grain growth in 2014
grain growth2015	Data on single grain growth in 2015
grain quality	Data on grain quality in 2014 & 2015 (CO2 x N study only)

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